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OPACITY OF STELLAR MATTER

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Abstract. New efforts to calculate opacity have produced significant improvements in the quality of stellar models. The most dramatic effect has been large opacity enhancements for stars subject to large amplitude pulsations. Significant improvement in helioseismic modeling has also been obtained. A description and comparisons of the new opacity efforts are given.

1. Introduction

Opacity has long been an issue in understanding stars. As long ago as 1926 Eddington identified opacity as one of two clouds obscuring stellar model calculations. At that time it was thought that bound-bound absorption was not a significant source of opacity. It was another 40 years before Cox and Stewart (1962; 1965; 1970) included bound-bound transitions and obtained increases in the Rosseland mean opacity exceeding a factor of three in some cases. The Cox-Stewart opacities greatly improved the quality of stellar models and remained the standard for more than a quarter century. This work continued to be modified and improved by Cox and others at Los Alamos (Cox and Tabor 1976; Huebner et. al 1977). A detailed description of this first generation Los Alamos opacity (LAO1) is given by Huebner (1986).

Even though the LAO1 opacities helped elucidate many features of stars, a number of observations continued to resist explanation. For example, period ratios in classical Cepheid models were too low, the mechanism for pulsation in β-Cephei stars could not be identified, the calculated Li abundance in dwarf stars of the Hyades cluster was much less than observed, and simulations underestimated wind-driven mass loss in classical Novae. A number of studies found that these problems are sensitive to changes in opacity (Fricke, Stobie, and Strittmatter 1971, Petersen 1974, Stellingswerf 1978). However, the opacity increases needed seemed unrealistically large; 300% in the case of the classical Cepheids and the β-Cephi stars. Simon (1982) determined that increasing the opacity for temperatures above 1×10^5 K would be sufficient to resolve the Cepheid and β-Cephei problems. He speculated that problems with heavy element opacities could be responsible and issued a plea for their reinvestigation. A group at Los Alamos (Magee et al. 1984) were the first to respond. They concluded that such large increases in opacity were inconsistent with atomic physics. Nevertheless, two completely new efforts to calculate the opacity were undertaken.

One of these is the Opacity Project (OP), led by M. Seaton at Univ. College London, the other is our effort at Lawrence Livermore National Laboratory, known as OPAL. These efforts have obtained large increases in the opacity (Iglesias, Rogers and Wilson 1987; 1992; Iglesias and Rogers 1991; 1996; Rogers and Iglesias 1992; Seaton et al 1994) which helped resolve a number of long-standing puzzles (Rogers and Iglesias 1994). The differences between OP and OPAL opacities are generally small compared to the differences with the older LAO1. An important exception is with solar interior opacities where OPAL obtained modest increases over LAO1, while OP is 40% lower. The decrease seems incompatible with heliosismology (Bahcall and Glasner 1994; Tripathy, Basu and Christensen-Dalsgaard 1997) and has been attributed to approximations in the OP calculations (Iglesias and Rogers 1995). A second generation of Los Alamos opacities (LAO2) have recently been released (Magee et al. 1998). In addition to the new stellar interior opacity calculations, there have been several new efforts to calculate surface opacities (Sharp 1993, Alexander & Ferguson 1994).

2. Brief Description of OPAL and OP

The calculation of opacity involves four distinct disciplines: equation of state (EOS), atomic physics, spectral line broadening, and plasma collective effects. The LAO1 opacities were calculated with an *ad hoc* model of the EOS and mostly hydrogenic approximations to the atomic physics. The new OP and OPAL opacity efforts are based on improved theoretical methods in all four of the disciplines mentioned above. In the following the improved physics and its impact on opacity are briefly described. More detailed accounts can be found in Rogers and Iglesias 1992, Iglesias and Rogers 1996, and the book by the OP team (Seaton et al. 1995)

Calculation of the EOS is logically the first step in the calculation of opacity, since this gives the state occupation numbers. Typically this part of the calculation has been based on simple *ad hoc* methods. New EOS methods used by OPAL (Rogers 1986; Rogers, Swenson, and Iglesias 1996) and OP (Däppen et al. 1987, Hummer and Mihalas 1988) have been instrumental to theoretical interpretations of the helioseismic data (Däppen; Christensen-Dalsgaard; Dziembowski; this volume).

Although differences in EOS models have in general not significantly affected astrophysical opacities, differences in bound state occupation numbers are a primary reason for OPAL opacity enhancements near the base of the solar convection zone (Iglesias and Rogers 1991). It is also one of the reasons OP gets a smaller opacity than LAO1 and OPAL in this region (Iglesias and Rogers 1995; see also Sec. 3).

By far the most significant effect on opacity has come from improved calculations of bound-bound absorption that include much more detailed atomic data. The OPAL and OP groups chose different approaches for this part of the calculation. The goal of OPAL was solely to calculate opacity, whereas OP had the additional aim to produce a general purpose atomic database. A continuation of that effort known as the Iron Project is still in progress (Bautista and Pradhan 1997). For the required atomic data the OPAL group developed a parametric potential method that is fast enough to allow on-line calculations, while achieving accuracy comparable to single configuration Dirac-Fock self-consistent field calculations (Rogers, Iglesias, and Wilson 1988). This on-line capability provides flexibility to study easily the effects of atomic physics approximations; e.g. angular momentum coupling or data averaging methods. By contrast, the OP group uses first principle (non-relativistic) methods to construct detailed atomic databases (Seaton 1987; Seaton et al. 1994). The large increase in the iron opacity obtained with the LS coupling scheme compared to calculations that neglect term splitting suggested that fine structure is also important (Rogers and Iglesias 1992). OPAL opacities calculated since 1992 include spin-orbit effects in full intermediate coupling (Iglesias, Rogers & Wilson 1992), while OP (Seaton et al. 1994) uses an approximate method that does not include spin changing transitions (see Fig. 1 of Rogers and Iglesias 1994). On the other hand, the OPAL calculation assumes single configurations, while OP includes configuration-interaction effects in both the bound-bound and bound-free calculations. Configuration-interaction is most important for atoms and near neutral ions.

The OPAL calculations include degeneracy and plasma collective effects in the free-free absorption using a screened form of the parametric potentials, whereas these effects are neglected in OP. Both OPAL and OP include collective effects in Thomson scattering (Boercker 1987). The OPAL spectral line broadening for one, two, and three electron ions is computed with a suite of codes provided by Lee (1988) that include linear

Stark theory. For all other transitions the OPAL calculations use Voigt profiles where the Gaussian width is due to Doppler broadening and the Lorentz width is due to natural plus electron impact collision broadening (Dimitrievic and Konjevic 1980). The OP approach is similar (Seaton 1987) except that for spectral lines not subject to linear Stark effect OP uses widths from quantum-mechanical close coupling calculations (Seaton 1988), which are similar to those used by OPAL.

The improved line broadening has in general had a small effect on opacity. One important exception is Stark broadening of hydrogen. LAO1 used the theory of Griem (1960) which gives lines that are much too broad compared to experiment (Wiese 1972). The OP and OPAL hydrogenic lines agree well with the data and result in an opacity reduction for Population II compositions around log T=4.8. Cox (1990) showed that this reduction in opacity in conjunction with a modest increase in opacity for logT ≈ 5.3 removes several long-standing puzzles in models of RR-Lyrae stars.

3. New Opacity Data

The latest OPAL and OP calculations of the Rosseland mean opacity, κ_R, are compared in Fig. 1 for various values of logR, where R=density/T_6^3 and T_6 is temperature in megakelvin. Although OPAL includes 19 metals while OP includes 15, the extra elements do not substantially affect the comparison. Both codes predict similar, but slightly shifted, bumps near log T≈5.3 due to millions of transitions originating in M-shell iron. This feature is completely absent from the older Los Alamos opacities (see Fig. 2 of Rogers and Iglesias 1994). This is the reason LAO1 failed to explain a wide range of stellar phenomena. Recently, the iron opacity bump was instrumental in predicting pulsational instability (Charpinet et al. 1996; 1997) in a newly discovered class of sdB subsequently confirmed by observations. The large increases in opacity predicted in the region of the iron bump have been corroborated by laboratory experiments. The first measurements were in the correct temperature range but at higher densities then occur in Cepheids (DaSilva et al 1992; Springer et al. 1992; Winhart et al. 1995). Recently, Springer et al. (1997) measured the iron opacity at conditions comparable to those in stellar envelopes. The OPAL frequency dependent opacities are in good agreement with all these experiments. Similar comparisons using OP data have not been reported.

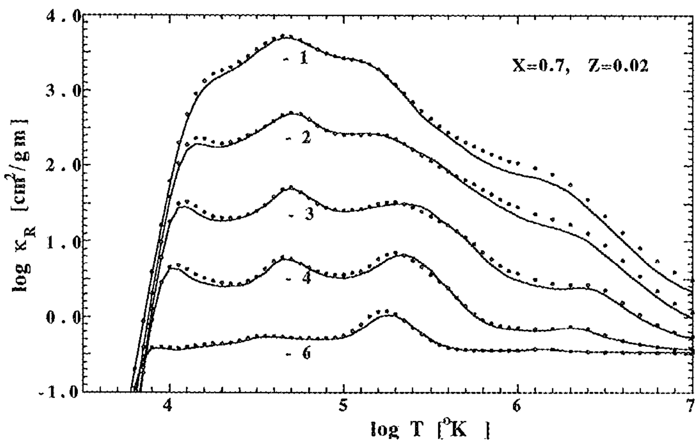

Figure. 1 Comparison of OPAL (dots) and OP (solid lines) Rosseland mean opacities at constant values of logR for the metal distribution used by Seaton et al. 1994 where X is the hydrogen mass fraction and Z is the metallicity.

Fig. 2 compares the ratio of OPAL to OP Rosseland mean opacities as a function of temperature for log R=-1.5, -3.5, and -5.5 for mixture having X=0.7, and Z=0.02. The largest differences occur near solar conditions, i.e., logR=-1.5. In this case, the ratio is near unity for log T < 5.6, but for higher temperatures the ratio increases rapidly to around 1.35. The major part of the discrepancy can be traced to incomplete photoionization data in OP (Iglesias and Rogers 1995). Fig. 3 shows the He-like carbon photoionization cross-sections from K and L shell states (Canuto et. al 1993). It is obvious that the 1s2s and 1s2p photoionization cross-sections do not include photoionization of the 1s electron, which should produce an edge in the vicinity of the $1s^2$ threshold. Figure 4 shows the OPAL monochromatic opacity for a representative solar mixture as a function of hv/kT for log T=6 and density of 0.01 g/cm^3, with and without the missing inner shell data in OP (Iglesias and Rogers 1997). The impact on the Rosseland mean from the missing inner shell photoionization data is similar in magnitude to the discrepancy shown in Fig. 2

Another source of discrepancy between OP and OPAL has been traced to an approximation in OP that affects the occupation numbers. Hummer and Mihalas (1988) assumed that the Holtsmark electric microfield, valid for randomly distributed ions, determines the probability a state is localized. In order to reduce computational expense they adopted an approximate form of the Holtsmark function. In a real plasma the

Coulomb interaction, cause the microfield distribution to peak at lower values of the field strength relative to Holtsmark. Consequently, the probability that a state is dissolved by the electric microfield fluctuations is reduced. Iglesias and Rogers (1995) show: 1) the OP approximation to Holtsmark is poor; 2) using the more realistic APEX microfield (Iglesias et al. 1985) significantly increases the OP occupation numbers for high lying states, bringing them closer to OPAL. Since the Hummer and Mihalas procedure and OPAL are based on different physical assumptions, the two

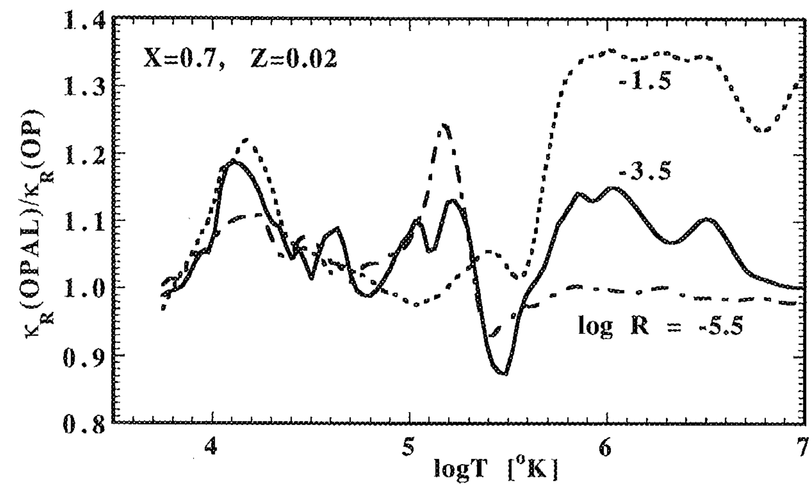

Figure 2. Ratio of OPAL to OP κ_R along a track that is close to solar.

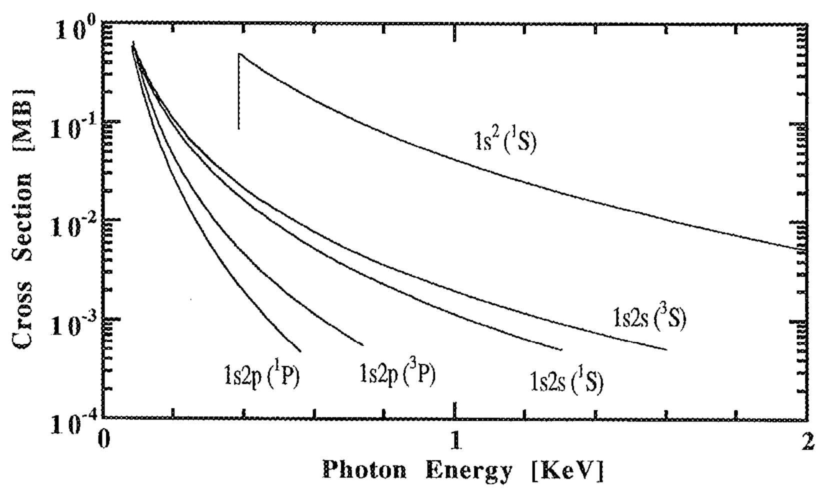

Figure 3. OP Photoionization cross-sections vs. photon energy for various configurations in helium-like carbon.

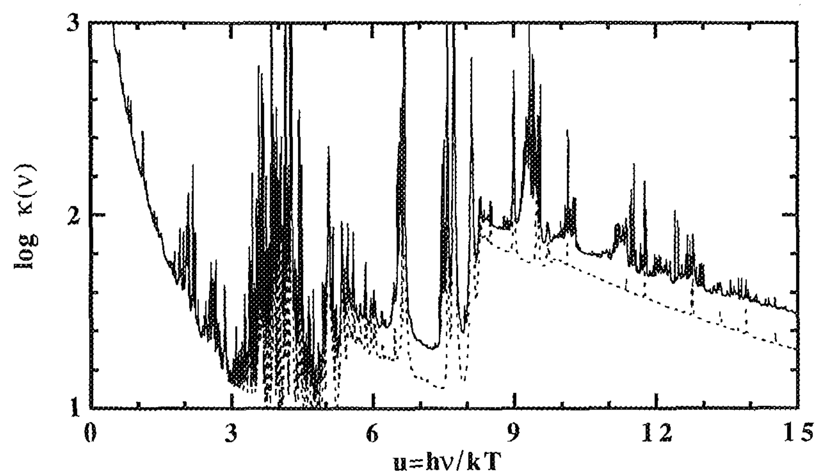

Figure 4 log κ(ν) vs. hν/kT with (solid line) and without (dashed line) the inner shell photoionization data missing from OP.

calculations can not be expected to agree exactly. Although these differences have only a small effect on the EOS, they may affect the opacity.

4. Sources of Missing opacity

Tsytovich et al (1996) suggested that a number of effects listed, in Table 1, have been neglected in existing calculations of solar interior opacities. They estimated that these effects could decrease the solar center opacity by as much as 14%. However, several of these mechanisms have been investigated and shown to be already included or incorrect. Iglesias (1997a) showed that, contrary to the claims of Tsytovich et al. (1996), the effect of Raman resonance broadening (labeled *a*) is already included in the frequency integration over the dynamic structure factor in existing calculations. The new expressions for electron-ion Bremsstrahlung (labeled *b*) reported by Tsytovich et al. result from a misinterpretation of earlier work and actually reproduce existing results (Iglesias 1997b) while their calculations of inverse Bremsstrahlung (labeled *c*) predict incorrectly both the sign and magnitude of the relativistic correction (Iglesias 1996). Finally, Iglesias and Rose (1997) showed that the major corrections to Bremsstrahlung and Thomson scattering (labeled *d*) given by Tsytovich et al. are already included in the OPAL calculations and that remaining corrections not currently included are small. The unlabeled mechanisms in

Table 1 have not been independently evaluated, so there remains a potential 3.9% reduction in the solar interior from these sources.

Table 1

Effects and size of opacity correction obtained by Tsytovich et al. 1996.

Mechanism	$\delta\kappa_R/\kappa_R$
Broadening of Raman resonance (*a*)	-2.0
Relativistic collective scattering	-0.1
Stimulated scattering and frequency diffusion	-3.0
Collective Bremsstralung (*b*)	-0.1
Relativistic Bremsstralung (*c*)	-4.7
Density inhomogeniety	-0.1
Refractive index (*d*)	-0.1
Quantum recoil scattering	-0.7
Ion correlations (*d*)	-1.5
Electron degeneracy (*d*)	-2.0
Total	-14.3

In addition to the effects proposed by Tsytovich et al., there are a number of other possible sources of opacity not included in OP and OPAL; e.g., electron-electron Bremsstrahlung (Maxon 1967) and two-photon absorption (More and Rose 1991). Furthermore, the current calculations are carried out in the single atom approximation. At high density there could be effects due to particle clustering beyond those already included in line-broadening.

In addition to new physics, some aspects of the current calculations may need improvement. For example, measurements by Glenser and Kunze (1996) of 2s-2p transitions in Li-like B indicate that, in this specific case, OPAL and OP may underestimate the line widths by a factor of two. Griem, Ralchenka, and Bray (1998) have challenged the experimental results, so that this issue is unresolved. Fortuitously, solar opacities are not very sensitive to line widths (Iglesias and Rogers 1991)), but a factor of two change in the line widths could affect Cepheid Variable opacities by 10% (Rogers and Iglesias 1992).

5. Composition

Until recently solar models have considered convection to be the only mechanism for material motion. However, gravitational settling and thermal diffusion have been found to improve agreement with observations and are becoming part of the standard model (Bahcall and Pinsonneault 1992; 1994; Guenther and Demarque 1997; Guzik and Swenson 1998). Diffusion is found to produce abundance changes of order 10% in the solar interior. Radiatively driven diffusion can also be an important source of material motion in some stars, e.g., hot white dwarfs. A number of calculations of radiation acceleration have recently appeared (Richer et al 1998; Seaton 1997). Using these new results Turcotte et al. (1998) have verified that radiation driven diffusion is small in the sun. Even so, it has been suggested that it should also be included in the best solar models (Christensen-Dalsgaard; this volume).

In addition to element diffusion, there are uncertainties in the observed abundances (Grevesse; this volume). Historically, improvements in the photospheric abundances have reduced the differences with meteoritic determinations. Figure 5 illustrates the affect on the opacity of increasing the O and Ne abundances individually by 15% for a track that is close to solar. These elements are seen to make their largest contribution at temperature around $2x10^6$ K, near the base of the solar convection zone. The effects are not large, but would show up in comparisons with helioseismic data. The most recent measurement of the solar neon abundance (Feldman and Widing 1990; Feldman; this volume) give a value that is 9% higher than Grevesse and Noels (1993) with an uncertainty of 15% due to atomic physics limitations.

6. Conclusion

The new opacity data has favorably impacted modeling of a broad range of stellar properties. This success provides a strong motivation to extend the calculations to cover a broader range of applications. For example, the temperature density range of white dwarfs and other dense stellar objects are partly beyond the range of the current tables, the elemental composition is not adequate to model s-process stars that have significant amounts of elements heavier than Fe, there are many applications requiring frequency dependent opacity data such as radiative levitation (Seaton 1997; Richer et. al 1997).

In the specific case of the sun, current opacity tables only allow for changes in the total Z. To facilitate the process of adding diffusion to the SSM it will be necessary to provide opacity tables that allow for variation of individual element abundances. Due to the stringent requirements set by helioseismology, and as abundance determinations improve, even small sources of opacity not included in the current calculations will need to be considered.

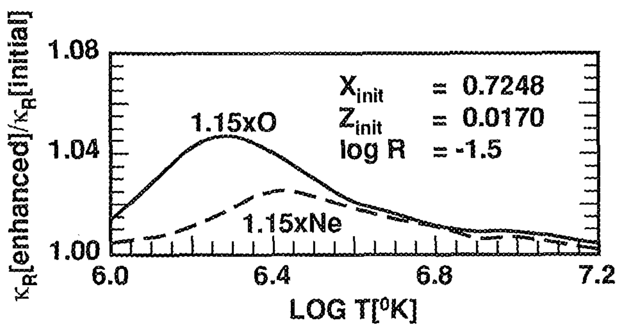

Figure 5. Effect on κ_R of enhancing O and Ne abundances by 15%.

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